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(54) **OPPORTUNISTIC DEFRAGMENTATION DURING GARBAGE COLLECTION**

(75) Inventors: **Srinivas Neppalli**, Irvine, CA (US); **Robert M. Fallone**, Newport Beach, CA (US); **William B. Boyle**, Lake Forest, CA (US)

(73) Assignee: **Western Digital Technologies, Inc.**, Irvine, CA (US)

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CPC ***G06F 12/0253*** (2013.01); ***G06F 3/064*** (2013.01); ***G06F 3/0611*** (2013.01); ***G06F 3/0613*** (2013.01); ***G06F 3/0647*** (2013.01); ***G06F 3/0676*** (2013.01); ***G06F 12/0888*** (2013.01); *G06F 2206/1004* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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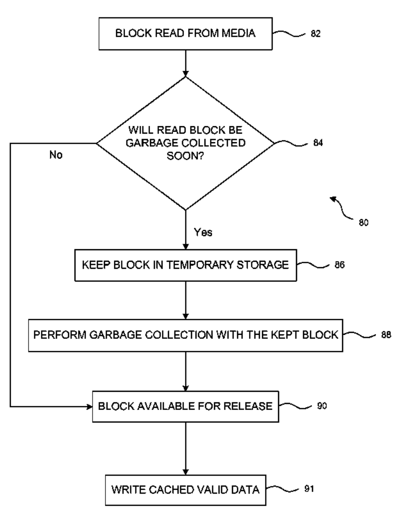
(57) **ABSTRACT**

The present invention is directed to systems and methods for opportunistically defragmenting a data storage device during garbage collection. During garbage collection, valid data is identified and cached in a buffer assigned to the garbage collection process. When the buffer has been filled or reached a threshold, the valid data in the buffer is then coalesced and rewritten back to the data storage medium. In addition, a translation table is reduced by updating its entries to indicate the new locations of the coalesced valid data.

17 Claims, 5 Drawing Sheets



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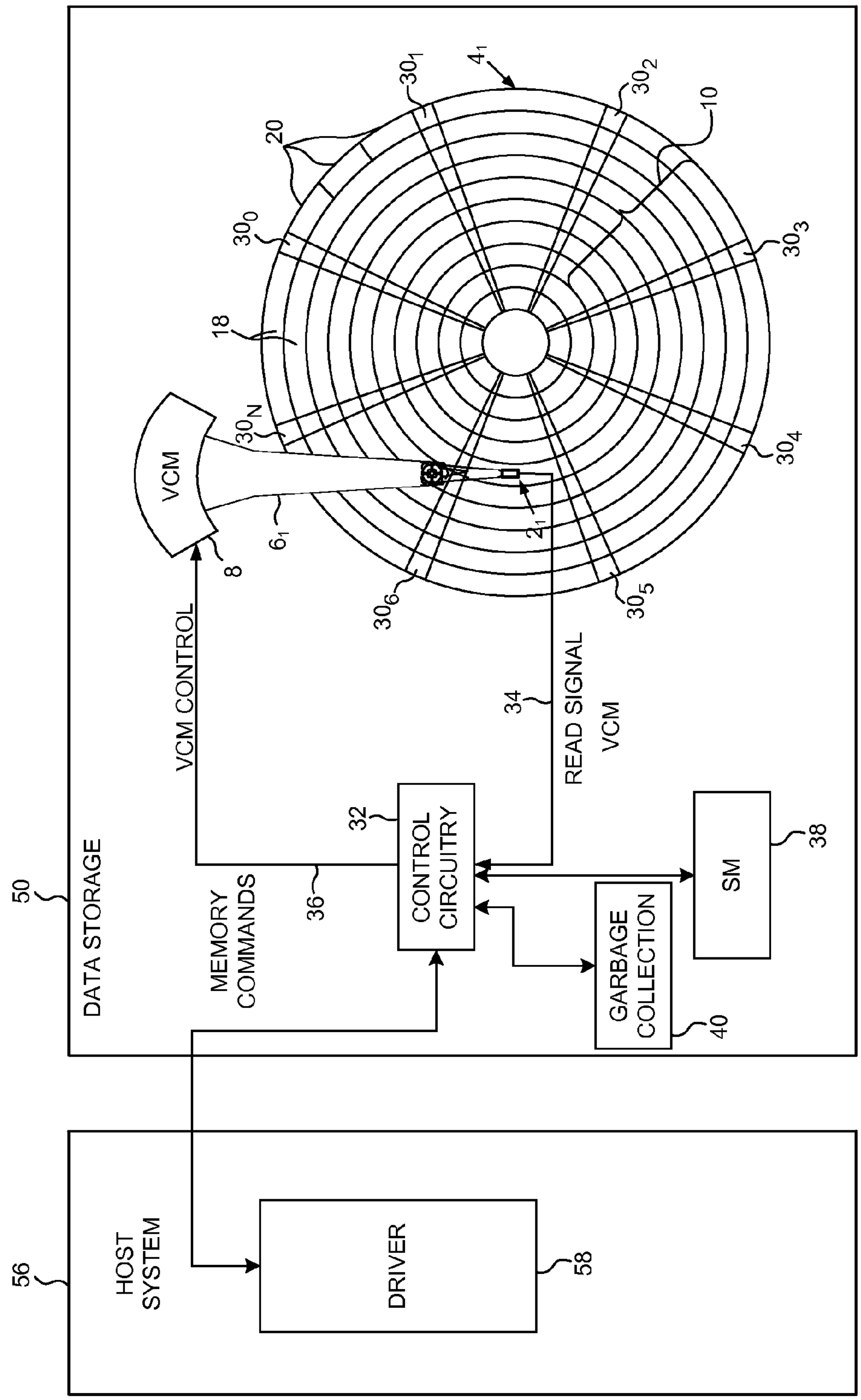

DATA STORAGE
50
VCM
VCM CONTROL
READ SIGNAL
VCM
MEMORY
COMMANDS
CONTROL
CIRCUITRY
SM
GARBAGE
COLLECTION
HOST
SYSTEM
DRIVER
56
58
32
34
36
38
40
8
10
18
20

FIGURE 1

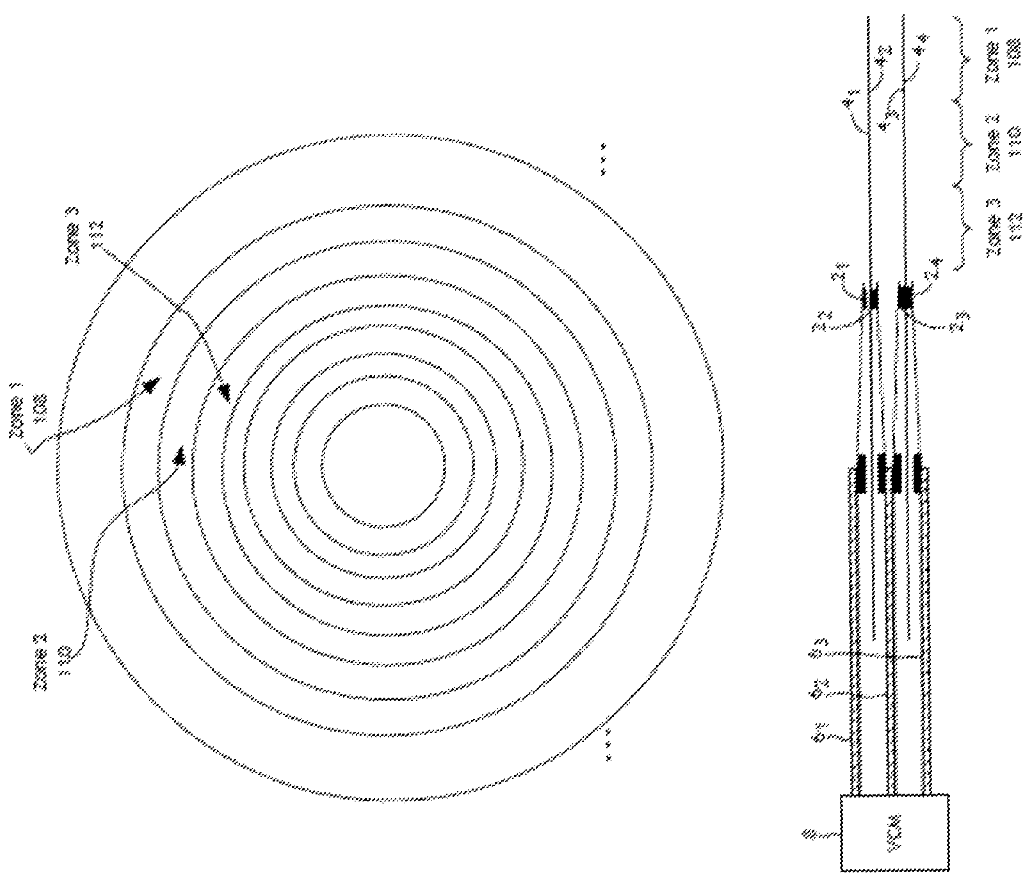


FIGURE 2

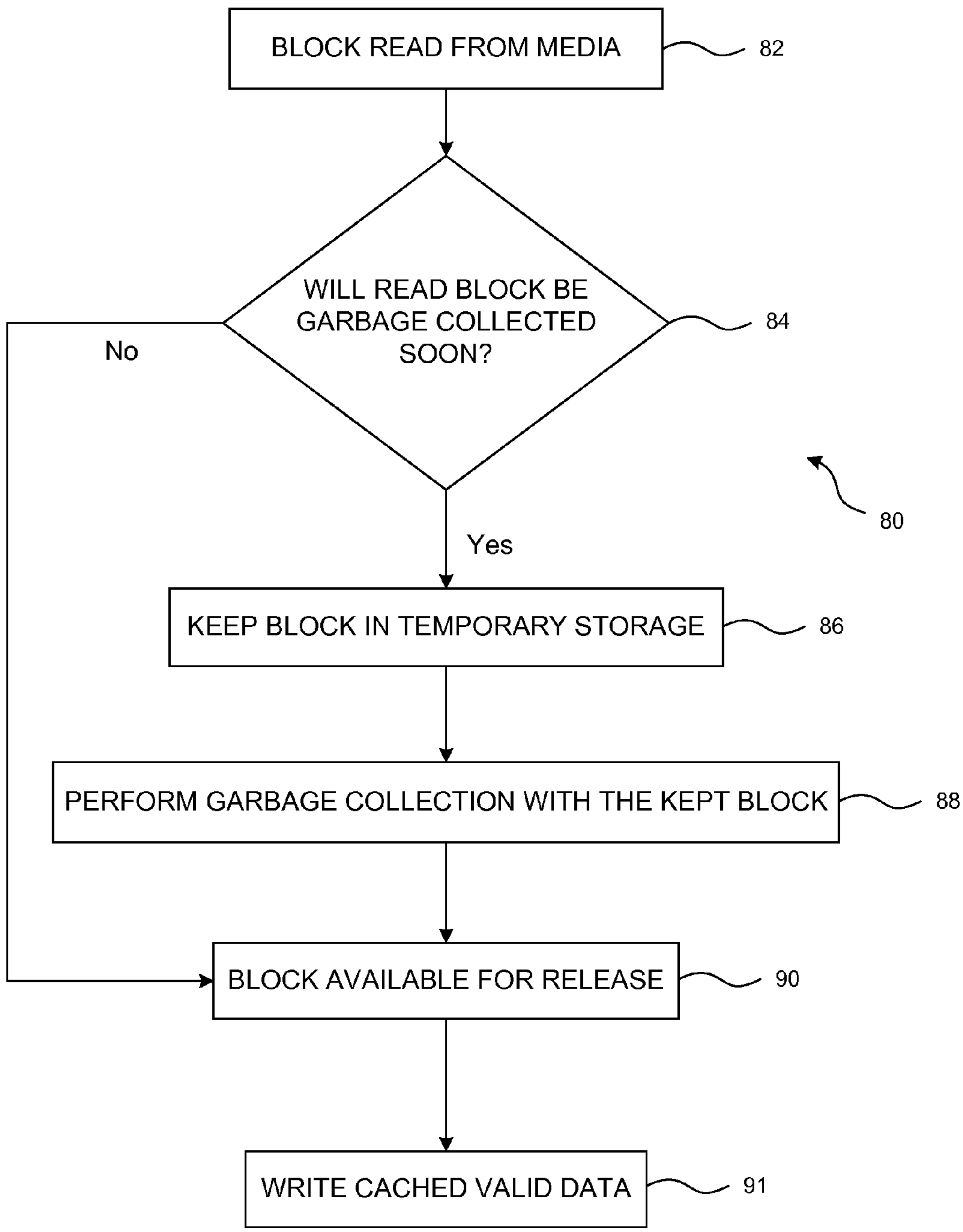
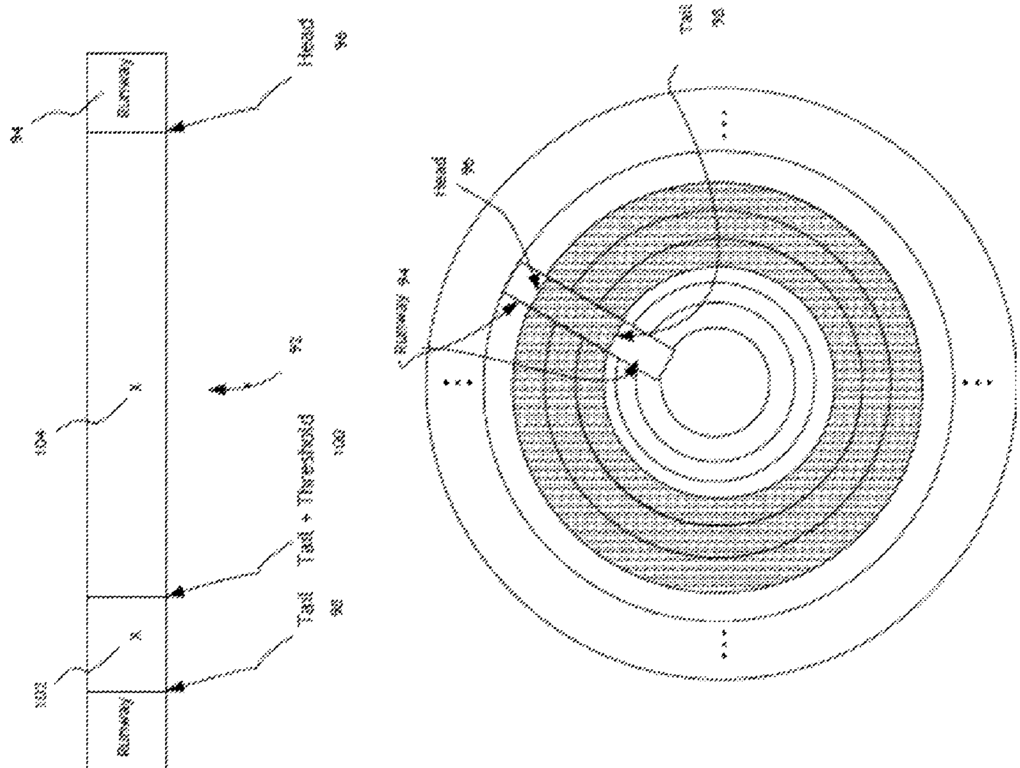

BLOCK READ FROM MEDIA
82
WILL READ BLOCK BE GARBAGE COLLECTED SOON?
84
No
Yes
80
KEEP BLOCK IN TEMPORARY STORAGE
86
PERFORM GARBAGE COLLECTION WITH THE KEPT BLOCK
88
BLOCK AVAILABLE FOR RELEASE
90
WRITE CACHED VALID DATA
91

FIGURE 3

FIGURE 4



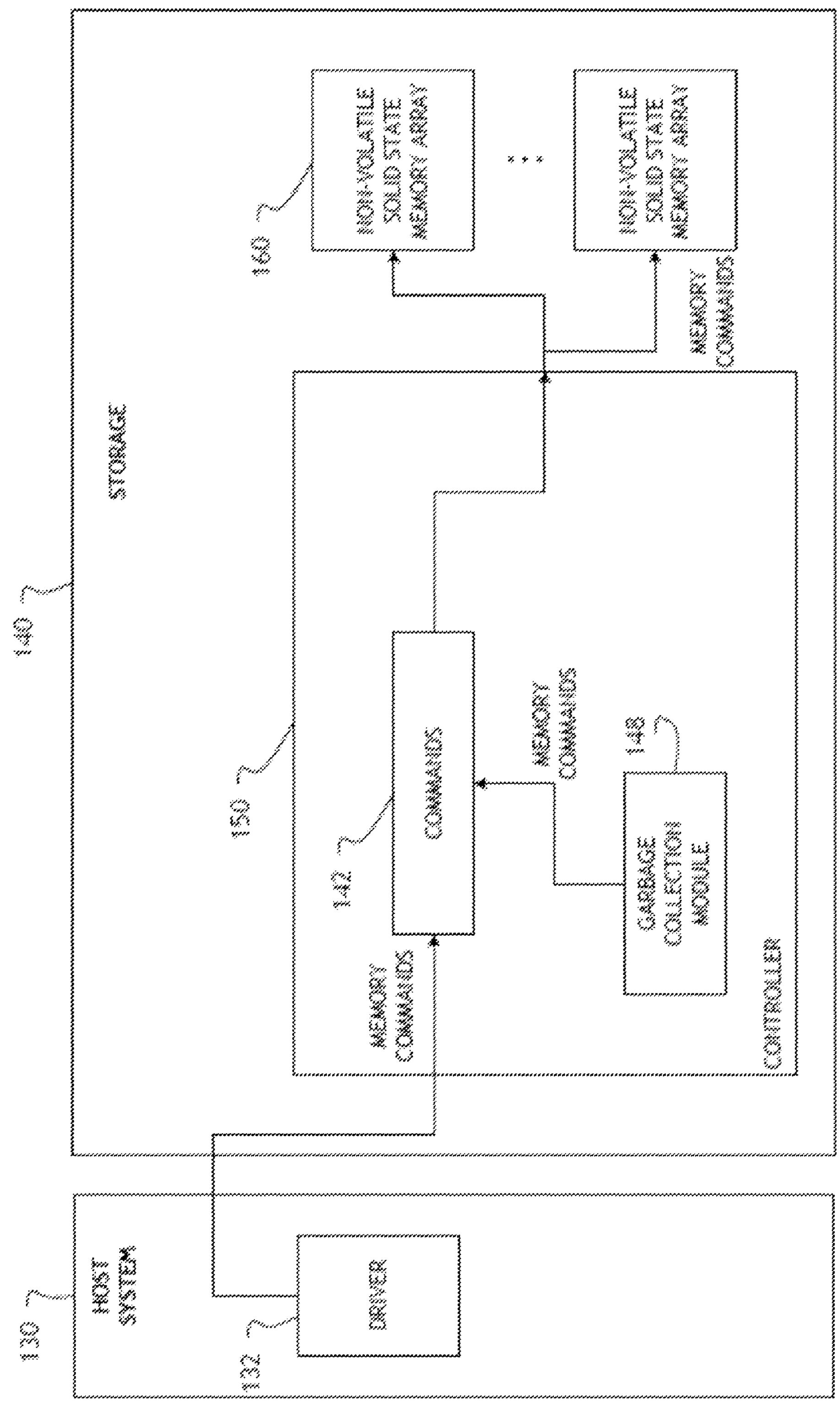

140
STORAGE
160
NON-VOLATILE SOLID STATE MEMORY ARRAY
. . .
NON-VOLATILE SOLID STATE MEMORY ARRAY
MEMORY COMMANDS
150
142
COMMANDS
MEMORY COMMANDS
148
GARBAGE COLLECTION MODULE
MEMORY COMMANDS
CONTROLLER
130
HOST SYSTEM
132
DRIVER

FIGURE 5

OPPORTUNISTIC DEFRAGMENTATION DURING GARBAGE COLLECTION

BACKGROUND

Garbage collection is often performed in data storage devices that implement uni-directional write policies. For example, some non-volatile solid-state memory devices and shingled disk drives both program or write data to the media in one direction, whether the incoming data from the host has random or sequential logical addresses. Because data for logical addresses can be located at any physical location, garbage collection is needed to reclaim locations on the media that no longer contain valid data for future writes. For example, in a shingled disk drive, if a track stores both valid and invalid data, the valid data may be copied by the controller as part of garbage collection to a new location so that the entire track can be made available for future write operations.

BRIEF DESCRIPTION OF THE DRAWINGS

Systems and methods which embody the various features of the invention will now be described with reference to the following drawings, in which:

FIG. **1** is a block diagram illustrating a disk-based data storage device according to one embodiment.

FIG. **2** is a block diagram illustrating a shingled disk storage device with a plurality of zones according to one embodiment.

FIG. **3** is a flow diagram showing a process executed by the garbage collection module and/or the control circuitry to optimize garbage collection and opportunistically perform defragmentation in accordance with one embodiment.

FIG. **4** is a block diagram further illustrating how data is determined to be invalid or garbage collected soon.

FIG. **5** is a block diagram illustrating a solid-state storage subsystem according to one embodiment.

DETAILED DESCRIPTION

The present invention is directed to systems and methods for opportunistically defragmenting a data storage device, such as a shingled magnetic disk drive, during garbage collection. During garbage collection, the identified valid data (e.g., data that is to be kept) is cached. The valid data is coalesced, and when the cached data has been coalesced or fills the cache, it is written back to the data storage medium to reduce the number of required disk operations. In one embodiment, the valid data found during the garbage collection process is written back such that it can be read by a single disk operation

Certain embodiments of the inventions will now be described. These embodiments are presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel methods and systems described herein may be embodied in a variety of other forms. Furthermore, various omissions, substitutions and changes in the form of the methods and systems described herein may be made without departing from the spirit of the inventions. To illustrate some of the embodiments, reference will now be made to the figures.

FIG. **1** shows a disk-drive based data storage device **50** according to one embodiment. The data storage device **50** includes a head $\mathbf{2}_1$ actuated radially over a disk surface $\mathbf{4}_1$ by an actuator arm $\mathbf{6}_1$, and a voice coil motor (VCM) **8** operable to rotate the actuator arm $\mathbf{6}_1$ about a pivot. The disk surface $\mathbf{4}_1$ comprises a host addressable area **10** with a plurality of data tracks **18**, wherein each data track **18** comprises a plurality of data blocks **20**.

In the embodiment in FIG. **1**, the disk surface $\mathbf{4}_1$ further comprises a plurality of embedded servo sectors $\mathbf{30}_0$-$\mathbf{30}_N$ that define the data tracks **18** in the host addressable area **10**. The data storage device **50** further comprises control circuitry **32**, which is operable to process a read signal **34** emanating from the head $\mathbf{2}_1$ to demodulate the embedded servo sectors $\mathbf{30}_0$-$\mathbf{30}_N$ and generate a position error signal (PES). The PES represents a radial offset of the head $\mathbf{2}_1$ from a target data track **18** in the host addressable area **10**. The control circuitry **32** is further operable to process the PES with a suitable servo compensator to generate a VCM control signal **36** applied to the VCM **8**. The VCM **8** rotates the actuator arm $\mathbf{6}_1$ about a pivot in order to actuate the head **21** radially over the disk surface $\mathbf{4}_1$ in a direction that decreases the PES. The control circuitry **32** is also configured to receive commands from a driver **58** in the host system **56**.

In one embodiment, the data storage device **50** further comprises a garbage collection module **40** for managing garbage collection operations. In another embodiment, the control circuitry **32** manages garbage collection operations. The management and execution of garbage collection operations will be further described below.

In one embodiment, the data storage device **50** further comprises a buffer in a memory, such as a semiconductor memory (SM) **38**, communicatively coupled to the control circuitry **32**. The SM **38** may serve as a cache for temporarily storing write data received from the host **56** via a write command and read data requested by the host **56** via a read command. The SM **38** can be implemented, for example, using dynamic random access memory (DRAM), flash memory, or static random access memory (SRAM).

In addition, the SM **38** may provide storage for a translation table used by the control circuitry **32**. The translation table provides a data structure for mapping the logical block addresses (LBAs) requested by the host **56** into physical locations on the data storage device **50**, such as on disk surfaces **4**. On data storage devices that implement shingled magnetic recording, such as those shown in FIG. **2**, commands from the host **56** are recorded sequentially, resulting in LBA indirection. Since there is no fixed location on the data storage device **50** for a given LBA, control circuitry **32** maintains the translation table to keep track of the locations of the LBAs. For example, when a LBA is rewritten, a newer copy of that LBA will be written in a new location on the disk surfaces **4**, and control circuitry **32** then updates the translation table to reflect the latest physical location of that LBA.

Data storage devices, including solid-state drives (SSDs) and shingled disk drives typically require garbage collection. This is due to the fact that LBAs for blocks of data are usually not rewritten to the same physical location they were before the rewrite operation. Since LBAs are rewritten in a new location, the old location becomes obsolete or invalid, and thus, may be considered “garbage”. The media and storage space consumed by the garbage should be reclaimed so that it can be reused.

FIG. **2** is a block diagram illustrating a shingled disk storage device with a plurality of zones according to one embodiment. One embodiment of the data storage device **50** may be a shingled-based disk drive in which the control circuitry **32** accesses at least part of the storage using log structure writes wherein a band of the data tracks are accessed as a circular buffer. In the shingled-based disk drive embodiment, data tracks are written in a shingled (overlapping) manner.

As shown, for example, the data storage device **50** is divided into multiple zones, including a zone **1** (**108**), a zone **2** (**110**), and a zone **3** (**112**). A plurality of heads 2_1-2_4 are actuated over respective disk surfaces 4_1-4_4 by a VCM **8** which rotates actuator arms 6_1-6_3 about a pivot. In one embodiment, each of disk surfaces 4_1-4_4 comprises a host addressable area **10** comprising a plurality of data tracks **18**. A zone may span multiple layers of the disk as shown. For example, zone **1** (**108**) may span a portion of the disk surfaces 4_1, 4_2, 4_3, and 4_4 as indicated by the bracket. Similarly, zone **2** (**110**) may span a portion of the disk surfaces 4_1, 4_2, 4_3, and 4_4 as indicated by the bracket.

According to one embodiment, the data storage device **50** is a shingled-based disk drive in which the control circuitry **32** accesses at least part of the storage using log structure writes wherein a band of the data tracks are accessed as a circular buffer. New data is written to the head (current data track), and during a garbage collection operation, valid data is relocated from the tail of the buffer (old data tracks) to the head of the buffer so as to free space for new write data. In the shingled-based disk drive embodiment, data tracks are written in a shingled (overlapping) manner.

FIG. **3** is a flow diagram showing a process **80** executed by the garbage collection module **40** and/or the control circuitry **32** to optimize garbage collection and opportunistically perform defragmentation in accordance with one embodiment. As noted, garbage collection requires moving blocks of data, which typically requires a read operation followed by a write operation. However, this shuffling of reading and writing data can negatively impact overall performance of the drive. Accordingly, since defragmentation also requires moving data, the embodiments take advantage of the read operation performed during a garbage collection process and optimize the rewriting of the user data. For example, when a buffer assigned for garbage collection process is full with valid data, the embodiments attempt to coalesce the data before it is written back to the media on the data storage device **50**. In addition, by coalescing the data, a fewer number of entries are required by the translation table, and thus, minimizing the size consumed by the translation table as well.

In addition, control circuitry **32** and/or garbage collection module **40** may be configured to balance the respective results of garbage collection versus defragmentation. In particular, in some instances, garbage collection may increase defragmentation and vice versa. For example, during defragmentation, data is moved, which thus results in garbage being created. Accordingly, in some embodiments, control circuitry **32** and/or garbage collection module **40** may be configured to optimize one process over the other. Thus, the control circuitry **32** and/or garbage collection module **40** may be configured to modify how data is written back to the disk surface **4** to overwrite areas that are marked as garbage based on a number of factors, such as vicinity, track location, head position of head **21**, etc.

For example, during garbage collection, the control circuitry **32** and/or garbage collection module **40** may opportunistically create garbage to help defragmentation. As another example, during garbage collection, the defragmentation process may take advantage of "gaps", e.g., relatively isolated blocks of invalid data and fill in these gaps with coalesced data from the cache. This fill-in process can be based on proximity to valid data. In some embodiments, proximity can be based on seek operation, rotational tolerance of the head **21**, track location, and the like.

Referring now to FIG. **3**, in phase **82**, a memory block is read from the media of the data storage (e.g. the shingled disk drive). In one embodiment, the memory block may be read in response to a read command from the host **56**. In other embodiments, the memory block may be read in response to other commands generated by the data storage device **50** (e.g. wear leveling command if the data storage is a solid-state memory device).

In phase **84**, the block retrieved from the read operation is analyzed to determine it is valid, invalid, and/or will be garbage collected soon. The determination of a block's status is further described below with reference to FIG. **4**.

In phase **86**, if the read block is determined to be valid (i.e., data that should be retained), the data contents of the read block are cached. For example, the contents of the read block may be stored in a cache assigned in the semiconductor memory (SM) **38**. In one embodiment, data from the read block may be placed in a read cache as part of processing the read command, or may already exist in the read cache because of a prior read command. In one embodiment, the valid data cached in SM **38** may be coalesced such that valid data that was previously fragmented is now defragmented. For example, the valid data may be cached so that it is contiguously stored on the disk. Of course, the valid data may be coalesced and reordered by the control circuitry **32** when rewritten.

In addition, in phase **86**, read blocks for invalid (i.e., data that can be flushed), may also be may be stored in the semiconductor memory (SM) **38**. In one embodiment, the data from the read block is tagged with a "dirty" flag/bit that is used by the read cache to mark data that should be retained for later flushing to the disk. In one embodiment, the data from the read block is tagged with a special flag/bit in place of or in addition to the "dirty" flag/bit to enable the read cache to differentiate data from the read block (which will be used for garbage collection) from other data that should be retained for flushing to the disk in the normal course of operation. In either case, in the embodiment with the read cache, the garbage collection module **40** and/or the control circuitry **32** may prevent data from the read block from being flushed from the read cache during the normal read cache flushing cycles. The read cache may thus implement different flushing policies for the different types of data.

In phase **88**, garbage collection is then performed on the blocks of invalid data cached in phase **86**. For example, the blocks may be flushed to disk.

In phase **90**, once garbage collection is performed, the contents of the read block are made available for release. In the alternative, if the read block is determined to not be garbage collected soon in phase **84**, the process **80** skips to phase **90**, where the contents of the read block are made available for release.

In phase **91**, the control circuitry **32** then writes the cached valid data in the SM **38** back to the disk surfaces **4** such that fewer disk operations are needed to retrieve the blocks when requested by a next read command. In one embodiment, the control circuitry **32** writes the cached data back to the disk surfaces in coalesced form such that the blocks are contiguously or substantially contiguously located on the disk surfaces **4**. That is, the blocks for data requested by the read command are rewritten in a contiguous manner on the disk surfaces **4**. That is, the blocks of data are written to physically adjacent locations on the disk surfaces **4**.

For example, in one embodiment, the control circuitry **32** issues a write command that comprises a number of logical block addresses (LBAs) and write data. In some embodiments, the control circuitry **32** may also write other information, such as, such as a timestamp. Of note, in a hybrid drive embodiment, metadata may be stored in flash memory while user data is stored on the disk.

The rewriting of the valid data in coalesced form may be triggered based on a number of factors. For example, the cache for valid data in SM **38** may be configured with a fixed size, such as 32 megabytes. Accordingly, once this cache for valid data reaches a threshold, such as 90%, 80%, etc., the control circuitry **32** may be configured to commence rewriting the valid data in coalesced form.

Furthermore, the control circuitry **32** may then optimize the translation table stored in the SM **38** based on the coalesced data that has been rewritten to the disk surfaces **4**. For example, the control circuitry **32** may compress one or more entries using a starting LBA of the coalesced data and a run length. The control circuitry **32** may also compress the translation table by encoding its entries to reduce its required size.

FIG. **4** is a block diagram further illustrating how data is determined to be valid, invalid, or garbage collected soon. Although the example shows data being written to the shingled disk storage device in a circular buffer, the garbage collection optimization embodiments of the invention are applicable to storage devices that implement other data access policies (e.g., zone-based access).

As shown, data is written to the disk-based storage device **50** in a circular buffer **92** with a head **96** and a tail **98**. Data is written in an area between the head and the tail, with new data being written in the direction from the tail toward the head. A runway **94** is shown in the circular buffer **92** after the head **96** and before the tail **98** where new data may be written to without overwriting valid data. In operation, new data is written at the head **98**, and the head **98** is moved forward into the runway area **92** after each write in one embodiment. The circular buffer **92** is circular in the sense that the runway spans the area between the head and the tail, and the head is moving toward the tail.

In one embodiment, garbage collection is performed at the tail to prevent the exhaustion of the runway **94**. Therefore, data located near the tail has a higher likelihood of being invalid or garbage collected in the near future. FIG. **4** shows two example data points **102** and **104**. In the determination made in phase **84**, the process **80** determines whether a block read from the media of the data storage device **50** should be saved for a later garbage collection operation. In the example of data point **102**, the determination would be positive since it falls into a range between the tail and a location of the tail offset by a threshold (tail+threshold). Since data in this range is likely to be needed soon for a garbage collection operation, saving it as part of fulfilling a read operation now (e.g., for a host read command) would eliminate the need to re-read the same data when the garbage collection operation is executed. On the other hand, data point **104** would not be saved for a future garbage collection operation since it falls outside of the range. In one embodiment, the determination needs to be made as there is typically limited space in the temporary storage where data can be saved.

In one embodiment, the threshold is based at least in part on the likelihood that a garbage collection operation will be needed soon. For example, a long runway may mean that garbage collection operation is not likely to be needed soon. Thus, the threshold may be set to be shorter. If the runway is short, then garbage collection is likely to be needed soon, and as a result the threshold may be set to be longer. The threshold may be measured by a number of memory units such as sectors, blocks, or tracks depending on the embodiments. In one embodiment, the threshold may be a fixed number of blocks from the tail, and if the read block falls in the range of the threshold, the read block will be saved for garbage collection. In another embodiment, the number of blocks from the tail may be adjustable, e.g., based on the size of the runway.

In one embodiment, additional data may be saved along with the read block. For example, in a shingled disk drive embodiment, if a host read command results in a read from a block “A,” data from the entire track in which block “A” is located may also be read and saved for future garbage collection operations.

In one embodiment, when garbage collection is needed, the read block may not be stored in temporary storage but instead written directly to a new location, such as the head **96**, as part of a garbage collection operation. For example, a read command from the host system **56** may trigger a garbage collection operation if the read data is near the tail and the runway **94** is running out of available space. In this case, the data is read from the target block of the read command, together with any adjacent blocks, and returned to the host and then written to a new location as part of a garbage collection operation. In another example, the read block is near the tail **98**, so all of the valid blocks from the tail **98** to the read block may be read and moved to the head **96** so that a garbage collection operation can increase the runway **94** while servicing a host command.

In one embodiment, each block in the data storage device **50** is time-stamped and the control circuitry **32** and/or the garbage collection module **40** is configured to maintain a list of blocks that are least recently used (LRU) (i.e., least recently written). The LRU list may be used to determine whether the data contents of a block should be migrated to another location as part of a garbage collection operation. In one embodiment, the contents of a block that appears on the LRU list are saved for migration. In one embodiment, the contents of a block with a time stamp that meets a minimum LRU criterion are saved for migration.

The various afore-mentioned methods of determining whether to keep data read as a part of a read command may be combined. For example, the LRU list may be combined with the list of zones sorted by the number of invalid blocks, so that instead of saving read data from any block from the top zones on the list, the determining process only saves data from those blocks that are listed on the LRU lists for the individual zones. Alternatively, the garbage collection module may garbage collect zones independent of the number of invalid blocks, such as by following a round-robin approach. In this embodiment, the read block may be migrated to another zone if it is determined that the zone the read block is currently located in is close to being next in order for garbage collection. Other garbage collection schemes may be used.

FIG. **5** is a block diagram illustrating a solid state memory-based data storage device according to one embodiment. As shown, a data storage device **140** includes a controller **150**, which in turn includes a command queue **142** and a garbage collection module **148**, which is configured to execute the at least some of the garbage collection operations described above. For example, the garbage collection module **148** may perform some or all of the functionalities performed by the garbage collection module **40** of the data storage device **50**. The garbage collection module **148** in one embodiment is configured to execute process **80** for each read command received in the command queue **142**. In one embodiment, the host command queue **142** receives memory commands from a driver **132** residing within a host system **130**, and the memory commands may include write and read commands issued by the host system **130**. As further shown in FIG. **5**, in one embodiment, the controller **150** executes the commands in the host command queue **142** in one or more non-volatile solid-state memory arrays **160**, as well as commands issued by the garbage collection module **148**. The commands from the garbage collection module **148** may be stored in the command queue **142** or in a separate queue.

The features and attributes of the specific embodiments disclosed above may be combined in different ways to form additional embodiments, all of which fall within the scope of the present disclosure. Although the present disclosure provides certain embodiments and applications, other embodiments that are apparent to those of ordinary skill in the art, including embodiments, which do not provide all of the features and advantages set forth herein, are also within the scope of this disclosure. Accordingly, the scope of the present disclosure is intended to be defined only by reference to the appended claims.

What is claimed is:

1. A method of defragmenting a data storage device, said method comprising:

receiving a read command from a host;

reading a first block of data stored in non-volatile media of a data storage device in response to the read command from the host;

determining a timing of garbage collection for the first block in response to reading the first block of data;

caching valid data of the first block in response to said determination;

coalescing the valid data;

identifying invalid data in a second block of data stored in the non-volatile media; and

rewriting back the coalesced valid data to the second block.

2. The method of claim **1**, wherein rewriting back the coalesced valid data to the second block comprises writing back the coalesced valid data in a contiguous sequence on the non-volatile media according to logical block addresses assigned to the coalesced valid data.

3. The method of claim **1**, wherein the first block of data is part of a circular buffer on the non-volatile media.

4. The method of claim **3**, wherein said determining comprises determining that the first block is located within a threshold number of memory units of a tail of the circular buffer.

5. The method of claim **1**, further comprising updating a translation table at least in part by encoding a starting logical block address and run length for new physical locations associated with the coalesced data.

6. The method of claim **1**, wherein said caching the valid data comprises caching the valid data in a buffer designated for garbage collection until a threshold is reached.

7. The method of claim **6**, wherein said coalescing the valid data is initiated by the data storage device when the threshold has been reached and comprises reordering the valid data based on logical block addresses in a sequential order.

8. A data storage device comprising:

a non-volatile medium;

a memory providing at least one cache for storing data from read operations;

an interface configured for communications with a host; and

a controller configured by a plurality of instructions, which comprise instructions for:

receiving a read command from the host;

reading valid data from a first block of data stored in the non-volatile medium in response to the read command from the host;

determining a timing of garbage collection for the first block in response to reading the valid data from the first block of data;

caching the valid data of the first block in response to said determination;

coalescing the valid data;

identifying invalid data in a second block stored in the non-volatile medium; and

rewriting back the coalesced valid data to the second block.

9. The data storage device of claim **8**, wherein the controller is further configured to coalesce the valid data based on logical block addresses assigned to the valid data.

10. The data storage device of claim **8**, wherein the controller is further configured to coalesce the valid data based on when the cache reaches a threshold.

11. The data storage device of claim **10**, wherein the controller is further configured to coalesce the valid data based on when the cache is full.

12. The data storage device of claim **10**, wherein the controller is further configured to coalesce the valid data into a contiguous sequential order according to logical block addresses assigned to the valid data.

13. A method of optimizing a translation table stored in a memory of a data storage device, wherein the translation table dynamically maps logical block addresses used by a host to physical locations on the data storage device, said method comprising:

receiving a first block of data from one or more read operations performed on a data storage device;

determining a timing of garbage collection for the first block in response to receiving the first block of data;

caching valid data of the first block in response to said determination;

coalescing the valid data;

identifying invalid data stored in a second block of data;

rewriting back the coalesced valid data to the second block; and

updating a translation table to indicate new locations of the coalesced data that has been rewritten back to the data storage device.

14. The method of claim **13**, wherein updating the translation table comprises determining a starting logical block address for the cached valid data and a run length.

15. The method of claim **13**, further comprising compressing the translation table to reduce memory consumed by the translation table.

16. The method of claim **13**, wherein updating the translation table comprises reducing a number of translation nodes used by the translation table.

17. The method of claim **13**, wherein coalescing the valid data comprises coalescing the valid data when a cache has been filled with identified valid data from a garbage collection process.

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